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OPTIMUM MIX OF CONSERVATION AND SOLAR ENERGY IN BUILDING DESIGN*

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ABSTRACT

A methodology is developed for optimally allocating resources between conservation and solar strategies in building design. Formulas are presented for a constrained optimum in which the initial investment is limited. The procedure is amenable to hand analysis if tables are available which give the Solar Savings Fraction as a function of the Load Collector Ratio for the locality. A numerical example is given.

INTRODUCTION

A methodology for developing the optimum solar energy system size given a fixed building load coefficient was developed by Duffie and Beckman[1] and in published work by Balcomb[2] and has been used extensively in solar cost optimization procedures. This results in a global optimum only if the designer was correct in choosing the initial energy conservation level. The formalism was extended in work by Brandemuehl and Beckman[3].

A significant improvement was made by Barley[4]. He developed a procedure for locating the global optimum consisting in first identifying the optimum solar heating fraction and associated load collector ratio and then optimizing the load subject to this condition. This procedure provides good design guidance if the builder is not constrained to a total initial investment of less than the optimum level but gives no indication of the optimum mix where the initial expenditure is constrained.

Empirical studies by Palmiter and Noll[5] and Sav[6] showed the superiority of one discreet strategy over another using specific numerical examples but did not develop a general methodology for determining an optimum mix.

A common problem with previous studies is that they require knowledge of both future fuel costs and the financial scenario which determines the present worth of a stream of future expenditures in order to locate an optimum. Many designers are reluctant to use the procedures because of their skepticism regarding such forecasts.

In prior studies no scaling law for energy conservation cost was employed and instead a few point calculations were used. The advantage of a simple scaling law is that it allows investigation of the entire three-dimensional cost surface providing insight into the tradeoffs being made.

COST EQUATIONS

Energy Conservation

Heat loss from a building is normally characterized as the sum of several heat flows each acting in parallel. For an opaque element, the "cost per R" is frequently used as follows:

$$\text{cost}_i = r_i R_i A_i - C_i \quad (1)$$

where r_i is the <u>incremental</u> cost per R per sq ft, R_i is the R-value, A_i is the area of the element, and $-C_i$ is the cost of the element extrapolated to $R_i = 0$.

The building load coefficient, L_i, is the area times the U-value,

$$\text{or} \quad L_i = 24\, A_i / R_i \quad (2)$$

where the 24 factor is to convert from a per hour basis to a per day basis. The cost of the element can then be put in a more generalized form as follows:

$$\text{cost}_i = b_i / L_i - C_i \quad (3)$$

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where: $b_i = 24 r_i A_i{}^2$ (4)

In most cases it is necessary to choose from among several different choices such as wall thickness options. Thus the cost equation is not a continuum as indicated in Eqn. 3 but actually a series of discreet points which might lie along a line indicated by Eqn. 3. For windows a similar scaling law might apply where the choice is the number of glazings to be used or the possibility of applying insulation on the windows at night. The values of b_i and C_i can be obtained by plotting a curve of $cost_i$ versus $1/L_i$ and choosing the best slope and intercept. The same scaling law is used for perimeter insulation and doors.

Infiltration represents a major part of the building load coefficient and little information is available on the cost of reducing the infiltration load. It is a logical conclusion, however, that the cost will behave according to the same type of inverse scaling law as Eqn. 3 with only discreet choices being available.

The total cost and the total load is the sum of the parts. It can be shown that minimum total cost varies inversely with the total load as follows:

$$cost = b/L - C_c \quad (5)$$

where:

$$L = \Sigma L_i \quad (6)$$

$$cost = \Sigma cost_i \quad (7)$$

$$b = (\Sigma \sqrt{b_i})^2 \quad (8)$$

$$C_c = \Sigma C_i \quad (9)$$

and:

$$L_i = L\sqrt{b_i/b} \quad (10)$$

$$cost_i = \sqrt{b_i b}/L - C_i \quad (11)$$

at the optimum

For the opaque elements:

$$R_i = \sqrt{24b/r_i}/L, \text{ at the optimum} \quad (12)$$

Example

Suppose discreet choices of conservation elements for a 1500 sq ft house are to be made from the following possibilities:

Element	Case	R	L (Btu/F·D)	Cost ($)
	1*	11.8	1759	0
walls 865 ft²	2	19	1093	132
	3	31	670	351
	4	60	346	880
	1*	16	2250	0
ceiling 1500 ft²	2	22	1636	140
	3	38	947	479
	4	71	507	1197
	1	U=1.64	2557	-304
windows 65 ft²	2*	U=1.08	1696	0
	3	U= .82	1279	295
	4	U= .65	1020	599
	1*	0	3300	0
perimeter 165 ft	2	5	1650	329
	3	10	1100	659
	4	15	825	989
	1*	1	960	0
doors 40 ft²	2	7.4	130	51
	3	12.4	77	91
	4	17.4	55	132
	1	0.2 ACH	943	2667
infiltration 12000 ft³	2	0.4 ACH	1887	1000
	3	0.7 ACH	3302	286
	4*	1.0 ACH	4717	0

*reference case

From these the following characteristics can be determined.

Element	A_i	C_i	r_i	b_i	b_i
Walls	865	215	.0211	379000	616
Roof	1500	349	.0145	784000	885
Windows	65	932	15.1	1530000	1237
Perimeter		330		1088000	1043
Doors	40	8	.200	7700	88
Infiltration		666		3144000	1773
Sum		2470			5642

therefore: $b = 5642^2 = 31832000$, $C_c = 2470$

There are $4^6 = 4096$ combinations possible from the array of original choices. The total cost and total load of each of these possible combinations is plotted on Fig. 1. The curve corresponding to Eqn. 5 is also plotted on this curve. One can see that the curve does represent the lower bound of choices, as claimed.

Cost of Solar Collection Area

In the normal fashion it is assumed that the add-on cost of solar collection area varies linearly with the area, as follows:

$$\text{cost of solar} = a A + C_a \quad (13)$$

where C_a is a fixed cost (usually employed for active solar systems) and A is the solar collection area.

The solar cost constants, a and C_a, vary widely with the solar system type and effectiveness. The following values will be used as an example:

$a = \$7.44/\text{sq ft}$
$C_a = 0$

These might represent typical costs which would be experienced for a passive system installation consisting of a Trombe wall which uses R9 insulation at night.

SOLAR SYSTEM PERFORMANCE

The solar performance curve must be determined for the local climate. This can be done using the F-Chart method for an active system or the LASL Solar/Load Ratio method for a passive system or through a detailed simulation analysis. In any case, the results should be expressed as solar savings fraction F, versus the load/collector ratio, LCR.

$$LCR = L/A \qquad \text{(Btu/DD-sq ft)}$$
$$F = \text{function of } LCR$$

CONSTRAINED OPTIMIZATION

The annual auxiliary energy required by the building is given by the following equation:

$$\text{Annual Aux.} = L(1-F)(\text{degree days}) \qquad (14)$$

For a constrained optimization situation the annual auxiliary energy is to be minimized subject to a limit on the initial cost given by the following:

$$\text{Initial cost} = aA + b/L + C_a - C_c \qquad (15)$$

Thus it is necessary to minimize the product, L(1-F), subject to a fixed initial cost. This can be solved by Lagrangian multiplier techniques or other methods to produce the following solution:

$$L_o = \sqrt{b\,LCR/(a\,R)} \qquad (16)$$
$$A_o = L_o/LCR \qquad (17)$$

where:

$$R = 1 + LCR(1-F)/D \qquad (18)$$
$$D = dF/d(1/LCR) \qquad (19)$$

These equations define the locus of points which represent an optimum mix between conservation and solar strategies.

Example

Table I lists values of F, LCR, D, and R for Dodge City taken from Reference 7 which lists such values for 219 cities for direct gain, Trombe wall, and water wall passive solar configurations with and without R9 night insulation. Corresponding optimum mix values of L and A are also shown in Table I determined from Eqns. 16 and 17 using the cost constants a and b from the previous examples. The total initial cost is then calculated from Eqn. 15 and the last column is the energy savings, compared to a conventional house for which the cost of conservation and the cost of solar are zero.

Now suppose that one had approximately $4000 to spend on solar and conservation strategies. What would be the optimum design? Looking in Table I, entries are found corresponding to a solar savings fraction of 60% which leads to an initial cost of $3943. Corresponding values of L and A are 7420 Btu/DD and 285 sq ft, respectively. The savings is 77% compared to the reference house.

In order to obtain L = 7420 Eqns. 10 or 12 can be employed and then the closest case can be located from among the discreet choices possible. This leads to the following table:

Element	$L_{opt.}$	closest case (s)
walls	810	2 or 3
ceiling	1164	2 or 3
windows	1627	2
perimeter	1372	2 or 3
doors	115	2 or 3
infiltration	2331	2
Sum	7420	

This process has narrowed the number of choices from 4096 to 16. Each of the 16 is optimal. The builder could pick any combination knowing that it is a good mix. The choice may well be based on preference or some consideration other than economics.

Figure 2 shows energy savings as a function of the cost of passive solar and the cost of conservation. The curved lines on the graph show energy savings, compared to the reference non-solar house which requires 65 million Btu/yr for heating. The dashed line shows an initial expense of $4000 for conservation and solar combined.

An optimum allocation (yielding a maximum energy savings) lies at the point where the dotted line is tangent to one of the energy savings curves. The maximum energy savings that can be achieved with a $4000 investment is 77% corresponding to $1850 spent on conservation and $2150 spent on solar. This point has been located using the procedure outlined earlier without the necessity of plotting the entire surface.

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TABLE I
OPTIMUM MIX PAIRS FOR DODGE CITY EXAMPLE

F %	LCR (Btu/DD sq ft)	D	R -	L Btu/DD	A sq ft	Costs Cons $	 Sol $	 Init. $	Energy Savings %
10	215	19.7	10.8	9219	43	980	320	1300	36
20	100	17.8	5.49	8824	88	1140	650	1790	45
30	63	16.0	3.76	8471	134	1290	1000	2290	54
40	45	14.6	2.85	8220	183	1400	1360	2760	62
50	34	12.7	2.34	7886	232	1570	1720	3290	69
60	26	10.2	2.02	7420	285	1820	2120	3940	77
70	20	7.2	1.83	6832	342	2190	2540	4730	84
80	15	4.4	1.68	6177	412	2680	3070	5750	90
90	10	1.8	1.56	5244	524	3600	3900	7500	96

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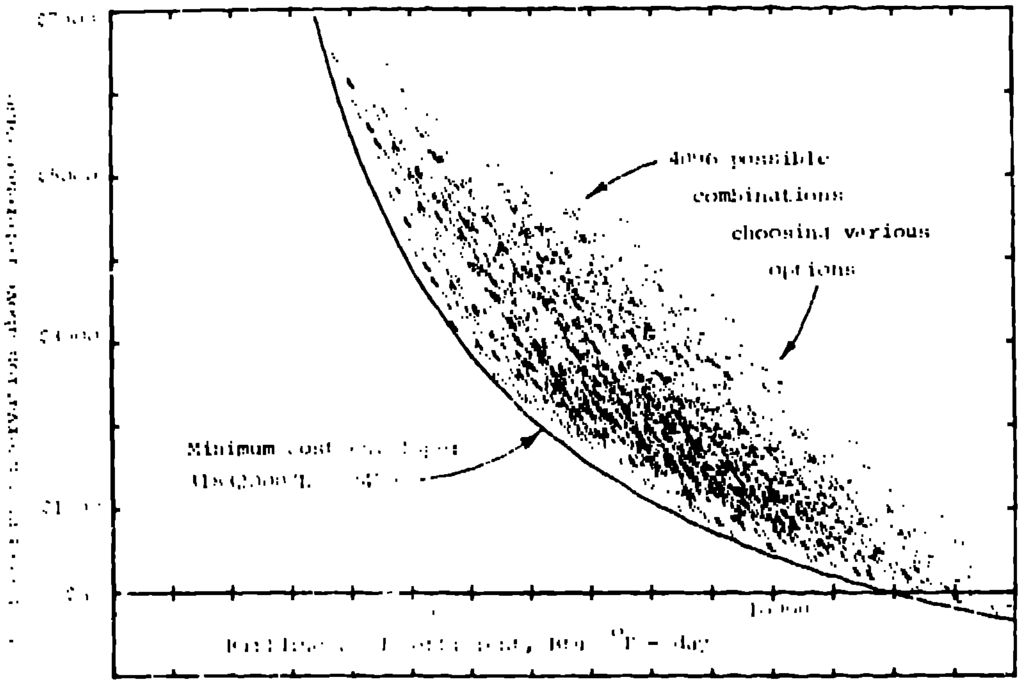

Figure 1. Cost of energy conservation, over and above the cost of the reference ... as a function of the Building Load Coefficient, L

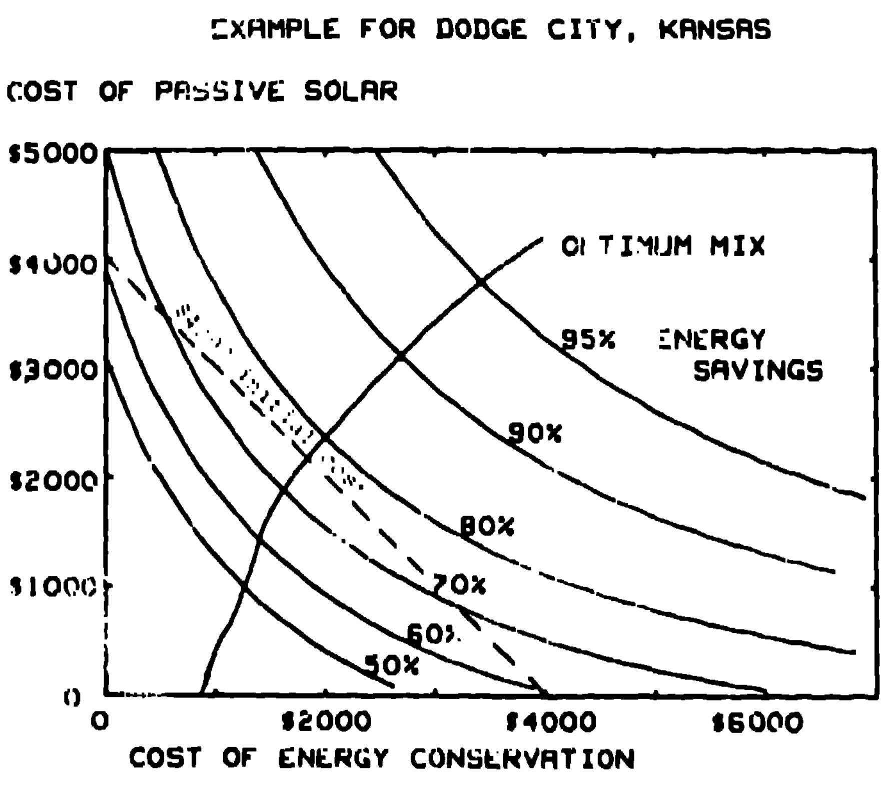

Figure 2. Performance map showing the energy savings expected for different initial expenditures.